100,000-Mile Evaluation of the Toyota RAV4 EV

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Abstract

In early 2000 Southern California Edison (SCE), in partnership with the Toyota Technical Center, initiated a test of five RAV4 Electric Vehicles (EVs) to evaluate the durability and reliability of their traction battery, and drive train, over a driving distance of 100,000 miles and beyond. The five vehicles in the project include three 1998 conductively charged RAV4 EVs and two 1999 inductively charged RAV4 EVs.

The 320 RAV4 EVs of the SCE fleet are used primarily by meter readers, service managers, field representatives, service planners and mail handlers, and for security patrols and carpools. As of June, 2003, and in 5 years of operation, the RAV4 EV fleet had logged more than 6.9 million miles, preventing the emission of about 830 tons of air pollutants, and of more than 3,700 tons of tailpipe carbon dioxide emissions.

SCE and Toyota began the test project in February 2000 to obtain data on operating costs, vehicle efficiency, maintenance requirements, battery life, charging issues and other factors that are specific to the long term use of EVs. Employees with long commutes were selected to drive the vehicles daily to and from work, at SCE's headquarters in Rosemead, or at the ISO 9001:2000 - certified Electric Vehicle Technical Center (EVTC) in Pomona.

On November 7, 2002, the first of the five RAV4 EVs under test to reach 100,000 miles had traveled the equivalent distance of Los Angeles to New York City 34 times without emitting a single tailpipe pollutant, or using a single quart of oil. In early June 2003 two other vehicles had reached the 100,000 mile goal. Data collected with the test vehicles, and the RAV4 EV fleet, are confirming that EVs with Nickel Metal Hydride batteries, and a mature drive train design, are compatible with a variety of mission requirements.

Keywords: Battery, Nickel Metal Hydride, Electric Vehicle

1. Introduction

In early 2000 Southern California Edison (SCE), in partnership with the Toyota Technical Center, initiated a test of five RAV4 Electric Vehicles (EVs) to evaluate the durability and reliability of their traction battery, and drive train, over a driving distance of 100,000 miles and beyond. The five vehicles in the project are three 1998 conductively charged RAV4 EVs and two 1999 inductively charged RAV4 EVs. The vehicle uses the Panasonic NiMH battery that has a nominal capacity of 95 Amp hours (Ah) at the C/3 rate. The average initial range of the RAV 4 EVs as received in the fleet is 94 miles on the EVTC's Urban Pomona Loop (UR1).

The following tests are performed with each of the project vehicles at 25,000-mile intervals:

1. A constant current battery capacity test at the rates of C/3 and C/5.
2. Two Urban Pomona Loop range tests (UR1)
3. One Freeway Pomona Loop range test (FW1)

4. A dynamometer test

The dynamometer tests are conducted at the California Air Resources Board (CARB) facilities.
A careful log of all the charging energy used by each project vehicle is kept.
The five-vehicle test is demonstrating the long-term durability of Nickel Metal Hydride batteries and of electric drive-trains. Only slight performance degradation has been observed to date with the highest mileage vehicles. Test data provide strong evidence that all five vehicles will exceed the 100,000-mile mark and SCE's positive experience points to the very strong likelihood of a 130,000 to 150,000-mile battery and drive-train operational life. This is achieved by full or mostly full range use after every charge. EVs can therefore match or exceed the lifecycle miles of comparable internal combustion engine vehicles.

2. Test Vehicles

Four Toyota RAV 4 EVs were originally chosen to take part in this long-term durability test. One 1998 conductively charged vehicle with an initial mileage of 38,982 miles (CON1) and three new 1999 inductively charged vehicles with fewer than 12 miles (IND 1, 2 and 3) were assigned to the project. In July 2001 one inductive RAV 4, IND 2, was involved in an accident and removed from the project. In January 2002 two conductive RAV4 EVs were added to the project (CON 2 and 3). They had been placed in service in 1998, as was CON 1. CON 2 had 73,642 miles and CON 3 73,949 miles when assigned to the project. CON 2 had had three modules replaced: module number 13 at 26,242 miles, modules 2 and 19 at 64,370 miles. The original modules were returned to Toyota.

Users with long round trip commutes were chosen to take part in this program. IND 1, CON 1, and CON 2 are based at the EVTC in Pomona, CA while CON 3 is based in Rosemead, CA. IND 3 was assigned to a new driver in September 2002 and is now driven mostly between Burbank and Pomona. The vehicles based in Pomona are driven during the day to add extra mileage. The RAV4 EV based in Rosemead has a longer daily round trip and does not require extra driving during the day. Energy usage is recorded with ABB kilowatt-hour meters. Table 1, below, summarizes key information on the test vehicles.

Table 1 – Vehicle List and Meter Location

ID	SCE Veh #	VIN #	Odometer as of 4-1-03	Meter ID	Meter Location
CON 1	24192	JT3GS10V7W0001332	104,321	02 143 074	On-board
IND 1	25560	JT3GS10V8X0001793	81,098	01 139 878	EVTC
				01 378 522	HOME
IND 3	25562	JT3GS10V1X0001795	81,458	01 378 530 01 378 531	Rosemead EVTC
				01 457 417	HOME
CON 2	24191	JT3GS10V9W0001333	100,907	02 143 068	On-board
CON 3	24193	JT3GS10V5W0001331	100,052	02 143 073	On-board

3. Test Results

Vehicle Mileage and Energy Usage

Table 2, below, shows the miles accumulated and the energy used by each vehicle from the start of testing to April 1, 2003.

Table 2 – Results From Start Date to April 1, 2003

Vehicle ID#	Start Date	Odometer At Start of Recording	Odometer As of 4-1-03	Miles Recorded In Project	Calculated AC kWh
CON 1	4-13-00	38,982	104,321	65,339	29,924
IND 1	2-2-00	299	81,098	80,799	33,110
IND 3	2-2-00	150	81,458	81,308	31,913
CON 2	1-1-02	73,642	100,907	27,265	12,536
CON 3	1-1-02	73,949	100,052	26,103	13,084

Baseline testing involves a number of battery capacity tests that add energy to the total AC kWh recorded but no mileage to the odometer. The calculated vehicle economy comes from a sample of daily drives each month. It is computed by taking the total AC energy recorded for charging after the sample drives and dividing it by the total miles driven. The results are compared to previous test reports and shown in Table 3 below. The average AC kWh/mile is 0.40. The inductive and conductive EVs recorded 0.38 and 0.42 kWh/mile respectively.

Table 3 – AC kWh/Mile on city and highway

	CON 1				IND 1				IND 3			
Date	Dec. 2000	July 2001	March 2002	Jan. 2003	Dec. 2000	July 2001	March 2002	Jan. 2003	Dec. 2000	July 2001	March 2002	Jan. 2003
AC kWh/mi combined City/Highway	0.39	0.43	0.42	0.37	0.43	0.37	0.38	0.39	0.34	0.36	0.37	0.39
AC kWh/mi City*	N/A	0.33	0.32	0.32	N/A	0.35	0.30	0.34	0.36	0.32	0.27	0.29

*Data acquired from 2 UR1 Range tests, Pomona Loop Data

	CON 2		CON 3	
Date	March 2002	Jan. 2003	March 2002	Jan. 2003
AC kWh/mi combined City/Highway	0.41	0.39	0.44	0.44
AC kWh/mi City*	0.30	0.32	0.29	0.31

*Data acquired from 2 UR1 Range tests, Pomona Loop Data

Vehicle efficiency can be affected significantly by driving style, air conditioning usage, and user's route. Some of the vehicles under test are driven on demanding routes. Table 4, shows the highest elevation increase of the test route of each vehicle.

Table 4 – Vehicle Elevation Gain

	Highest Elevation Increase (ft)
CON 1	760
IND 1	2,550
IND 3	2,360
CON 2	800
CON 3	740

Figures 1 to 5 show the complete elevation profiles of each test route.

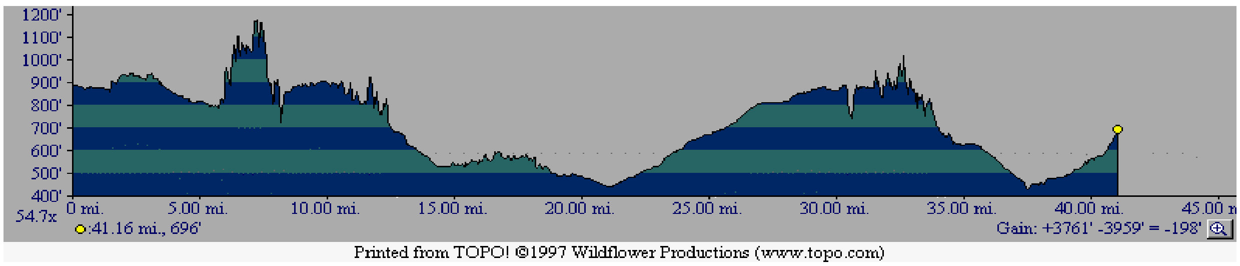

Figure 1 - Elevation Profile for CON 1, EVTC to Burbank

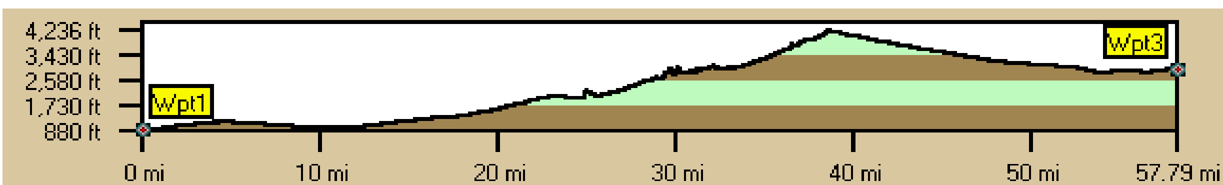

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Figure 2 - Elevation Profile for IND 1, EVTC to Apple Valley

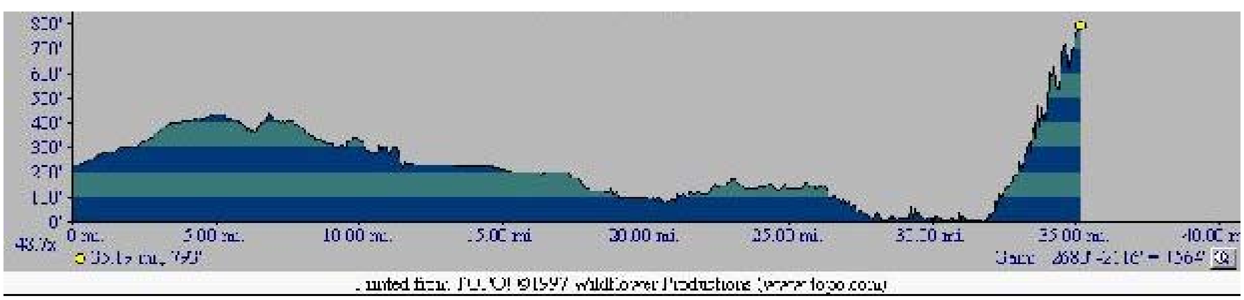

Figure 3 - Elevation Profile for CON 2, Rosemead to Pacific Palisades

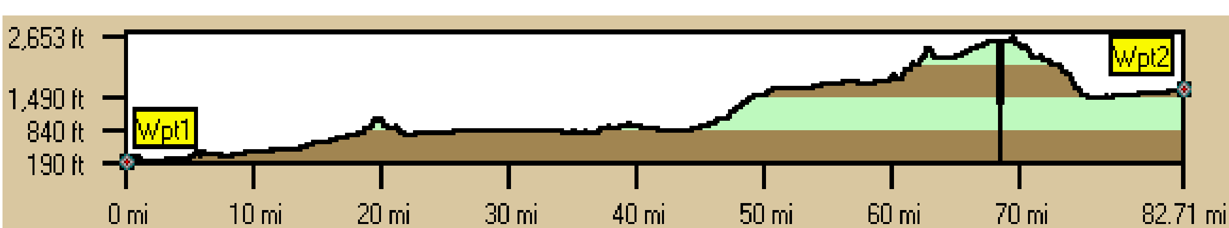

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Figure 4 - Elevation Profile for IND 3, Rosemead to San Jacinto

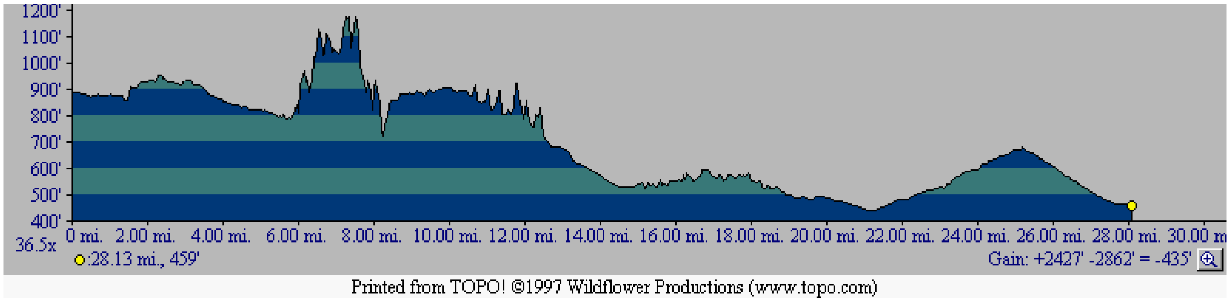

Figure 5 - Elevation Profile for CON 3, EVTC to San Gabriel

3.1 Dynamometer Testing

The most recent dynamometer tests were performed at the Haagen-Smit Laboratory (California Air Resources Board Facility [CARB]) in El Monte, California from December 12 to January 28, 2003.

3.1.1 Range Testing

Range testing on the dynamometer was performed using a modified test procedure based on the Society of Automotive Engineers recommended procedures for electric vehicle energy consumption and range testing (SAE J1634).

A combined City/Highway dynamometer range test cycle was used. The test consisted of two EPA Urban Driving Schedules (UDDS) followed by two Highway Fuel Economy Test Procedure (HWFET) cycles. The UDDS cycles simulated urban drives that were approximately 7.45 miles long, while the HWFET cycles simulated higher speed freeway drives that were 10.2 miles long. The average speed on the UDDS was 19.6 mph, and the maximum speed was 56.7 mph. The average speed on the HWFET was 48.3 mph, and the maximum speed was 59.9 mph. The dynamometer recorded vehicle speed, acceleration and distance traveled.

The test cycles were conducted as follows: Drive vehicle at 55 mph for one hour, perform two UDDS cycles, perform two HWFET cycles, and then drive until the vehicle can no longer maintain 55 mph.

Once the DC energy consumption per mile (DC Wh/mile) for each driving scenario was determined, the estimated range could be calculated (dividing the total DC kWh available from the traction battery by the DC kWh/mile). The combined city/highway range estimates are weighted proportionally to the amount of miles driven on each test cycle, and offer a more conservative range estimate than an arithmetic average of the highway and city discharge rates. CON 1, the 1998 RAV 4 with over 100,000 miles, had an estimated combined city/highway range 8% higher than in March and 1% higher than the test of July 2001. The 1999 inductive RAV4s, with over 75,000 miles, had insignificant changes in range. The estimated ranges of the two conductive vehicles were 119 and 95 miles respectively. All but one vehicle recorded an increasing range trend (CON 2).

Battery and charger efficiencies are determined by dividing the energy removed from the battery (measured in DC kWh) by the energy used to fully charge the battery (as AC kWh). The conductive and inductive vehicles averaged 83.9% and 83.6% efficiency respectively.

3.1.2 Acceleration Tests

Two acceleration tests (0 to 60 mph) were performed on the dynamometer at 100%, 80% , 50% , and 20% state-of-charge (SOC) to determine if there was a correlation between battery SOC and the power available to the motor. After each acceleration run the vehicles were driven at 55 mph until the next SOC was reached. The consistency of acceleration data suggests that the drive train controller maintains constant power in contrast with the available power strategy used with other types of EVs. Acceleration tests performed at the Pomona Drag Strip with other Toyota RAV4 EVs support this assumption.

Charging data collected after range and acceleration tests on the dynamometer were used to determine charger and battery efficiency. Table 5, below, shows these data. The average battery and charger efficiency of the conductive vehicles was 83.3% while the inductive EVs achieved 82.5%.

Table 5 – AC kilowatt-hour per Mile Vehicle Economy

	IND1				IND 3			
Date	12-00	7-01	3-02	1-03	12-00	7-01	3--2	1-03
Dyno Measured AC kWhr/mi Combined City/Highway	0.44	0.41	0.39	0.40	NA	NA	0.39	0.38
AC kWhr/mi City **	0.43	0.37	0.28	0.38	0.34	0.36	0.27	0.38

	CON 1				CON 2		CON 3	
Date	12-00	7-01	3-02	1-03	3-02	1-03	3-02	1-03
Dyno Measured AC kWhr/mi Combined City/Highway	0.49	0.39	0.43	0.43	0.33	0.43	0.43	0.43
AC kWhr/mi City **	0.39	0.33	0.31	0.32	0.30	0.32	0.29	0.31

**Data Acquired from Pomona Loop (UR1) Range Testing.

3.2 Urban Range, Freeway Range, and Capacity Testing

The baseline tests were initiated when the vehicles reached 25,000 miles. Each vehicle was subjected to two urban loop (UR1), one freeway loop (FW1), and two capacity discharge tests (at the C/3 and C/5 rates). The EVs were parked in the EVTC building after each driving test, and until the following morning to allow cooling of the traction battery and a full recharge. Pack temperature was noted around 5 PM, midnight and just before the start of the charge. The charge usually ended at the beginning of the normal workday and the tests were started during the hour that followed.

Table 6 shows results of the baseline tests for the three conductive RAV4s.

Table 6 - Capacity and Range Test Results for the Conductive Vehicles

	CON 1						CON 2		CON 3		
Range Date	*4-00*		*4-01*	*7-01*	*2-02*	*1-03*	*1-02*	*1-03*	*2-02*	*12-02*	*1-03*
UR1 (Average)	83[1]	N/A	74	93	87	81	65	53	67	54	104
Capacity Test Date	*4-00**	*8-00**	*12-00*	*6-01*	*3-02*	*1-03*	*1-02*	*1-03*	*2-02*	N/A	*1-03*
C/3 Ah out	90.6	73.2	86.6	89.8	84.2	72.1	78.9	80.6	79.1	N/A	87.8
C/3 Delta V	0.2	0.8	0.4	0.6	0.6	0.5	0.9	1.0	0.5	N/A	0.4
C/5 Ah out	90.0	76.3	83.2	92.4	88.1	75.9	85.1	81.0	83.9	N/A	90.9
C/5 Delta V	0.3	0.9	NA	0.6	0.7	1.4	0.8	1.0	0.6	N/A	0.5

[1]SOC gage may not have been set correctly. Flashing light on above red area.

* No cool down allowed before recharge.

3.2.1 CON 1 Test Results

The battery capacity and range numbers versus odometer readings are shown in Figure 6. Results from early tests without a cool down period are not included.

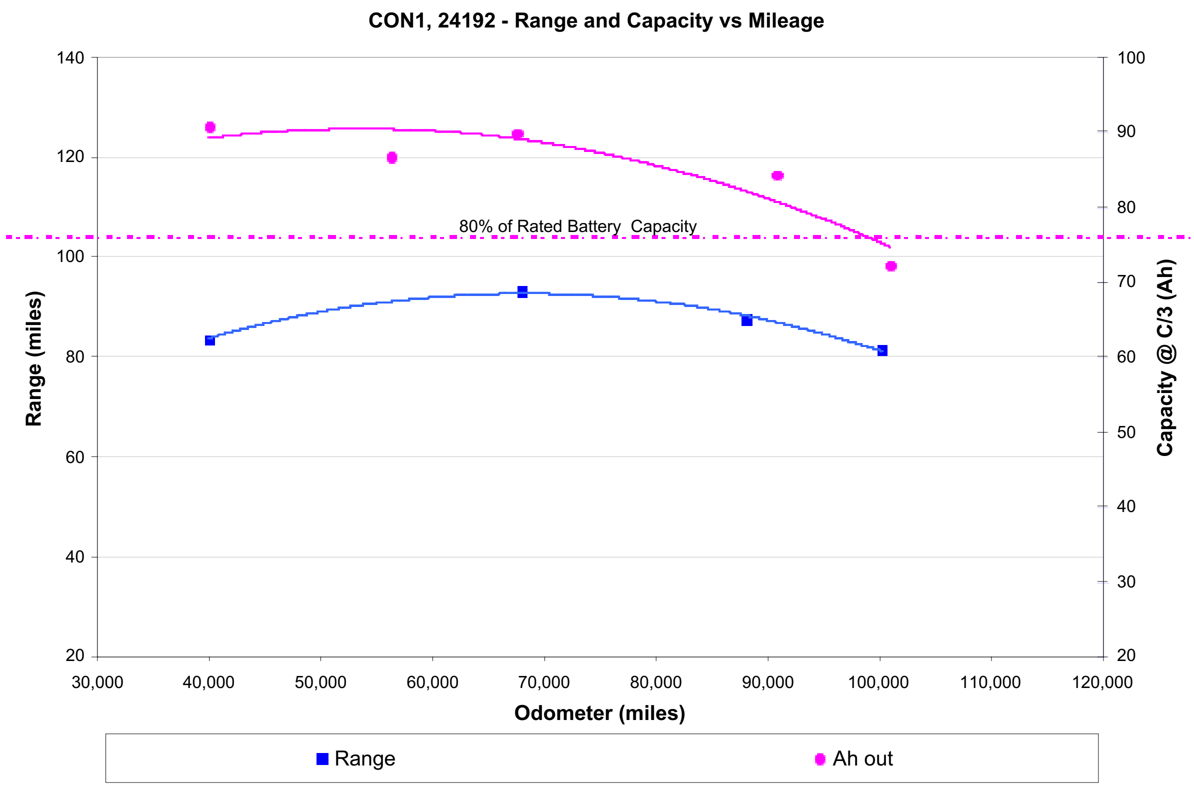

Figure 6 – CON 1 Range and Capacity versus Mileage

CON 1 has undergone more tests because of higher mileage, change of driver, and battery cool down testing. The cool down tests were implemented to see how long the battery took to cool before it would fully charge for the next day's testing. On hot days it was found that the vehicles would shut down charging due to battery temperature evolution. Based on this test, the vehicles were parked and the timer was set before the next day's test to allow for cooling.

CON 1 has experienced a 7% decrease of range and a 14% decrease of C/3 capacity since previous tests. This is due to one battery module discharging to 10V faster than the other modules. Range is still within 80% of the original number but battery capacity is below 80% of the rated number quoted by the manufacturer. Range and capacity will likely increase with a module replacement. Other modules show close voltage values during discharge.

3.2.2 CON 2 Test Results

Only two data points were collected with CON2. Battery capacity is 85% of its nominal value but shows an increase of 10.5% from the last test, and range has decreased by 28%, as plotted in Figure 7. This may be explained by the vehicle SOC gage setting, or by environmental conditions.

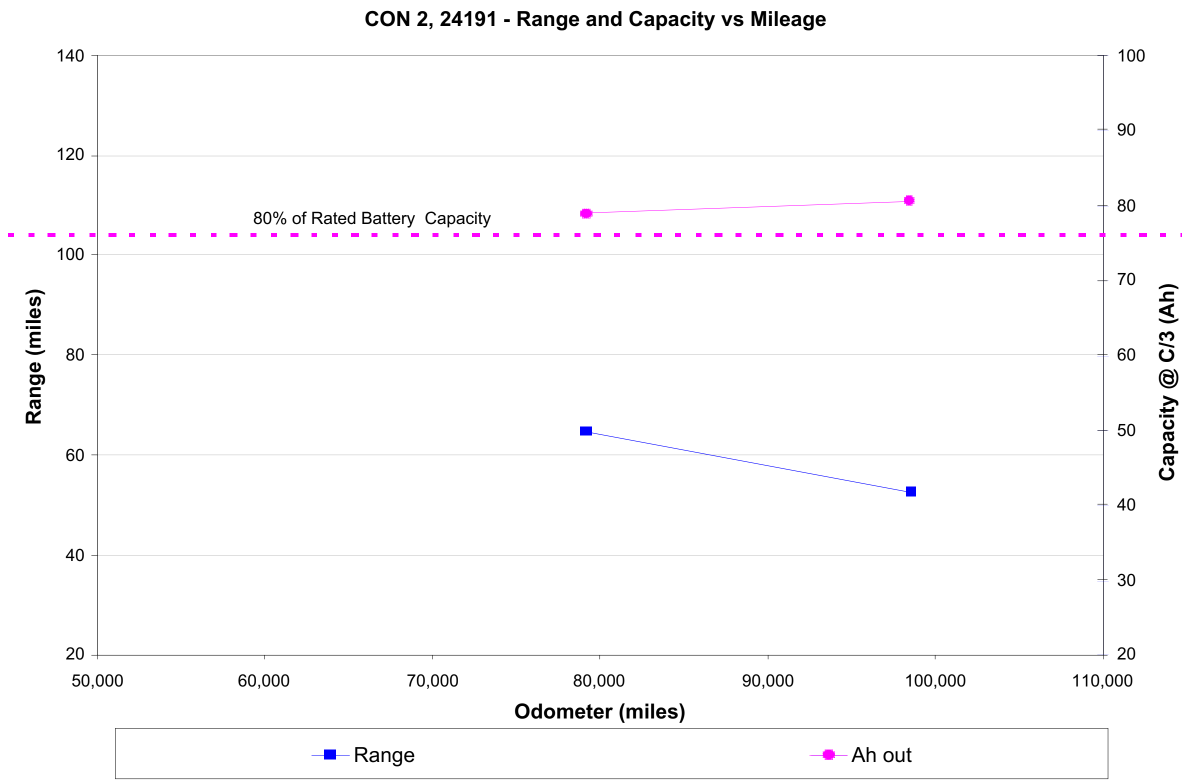

Figure 7 - CON 2, Range and Capacity versus Mileage

The Toyota Diagnostic Tester showed that module voltages were very close and that no anomalies were indicated. The vehicle SOC gage registered a low battery light in the green area (above 20% SOC) of the dial. A low battery light is normally expected at 20% SOC. Although the vehicle is running well, drivers have perceived a decrease in acceleration under full power conditions. CON 3 experienced a similar loss in range that was reversed as described below.

3.2.3 CON 3 Test Results

CON 3 had a range of 54.1 miles when tested in December 2002. This was a concern but no problem was detected by the diagnostic tester. It was suggested by service personnel that the SOC gage should be reset. A reset is performed by using the diagnostic tester to "Auto-Discharge" the traction battery until the controller automatically stops it at 0% SOC. The SOC gage is then reset to zero with the tester and the vehicle is fully charged to achieve a normal reading of 100% SOC. After this procedure, a UR1 range test was completed and yielded 54 miles. The project test protocol called for a capacity test which showed that the battery pack still had 92% of nominal capacity. Since battery capacity was still within specifications but the range had declined, an attempt was made to recover the range. Figure 8 shows total range recovery. Toyota would like to keep details about the recovery method employed confidential at this time.

The battery of CON 3 will be closely monitored during the remainder of the project.

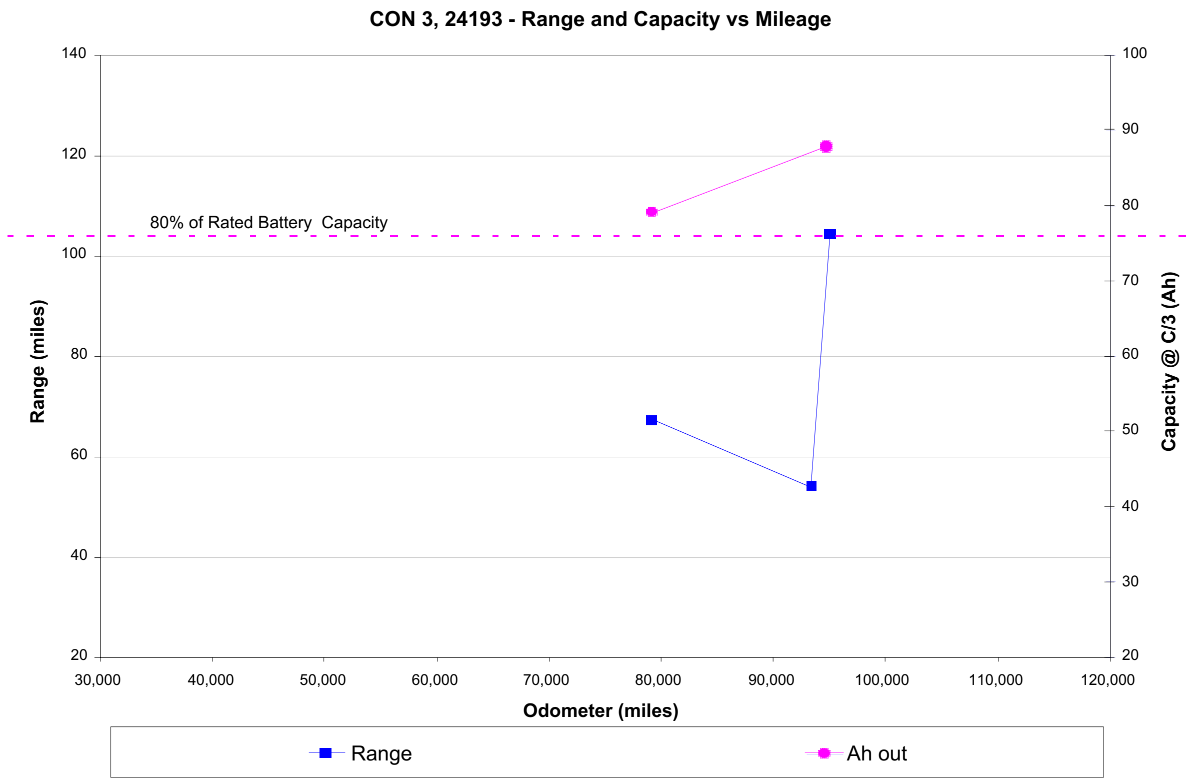

Figure 8 - CON 3, Range and Capacity versus Mileage

3.2.4 IND 1 and 3 Test Results

The two inductive vehicles are running well and showing little decrease in performance after 75,000 miles. Table 8 shows results since the beginning of testing in early 2000. After 25,000 additional miles the two vehicles show a decrease in range of 9% and 2%. Both have battery capacities in excess of 93% of the rated value.

Table 8 – Range and Capacity Tests for the Inductive Vehicles

	IND 1				IND 3			
Range Test *Date*	*2-00**	*5-01*	*1-02*	*1-03*	*2-00**	*6-01*	*2-02*	*1-03*
UR1 (Avg. of 2)	106	90	97	89	98	95	105	104
FW 1	89	75	94	83	89	NA	87	91
Capacity Test Date	*8-00**	*5-01*	*2-02*	*1-03*	*8-00**	*6-01*	*2-02*	*1-03*
C/3 Ah out	89.6	93.7	89.4	88.7	92.1	94.2	93.6	91.2
C/3 Delta V	0.5	0.3	0.3	0.5	0.2	0.2	0.3	0.4
C/5 Ah out	90.8	95.7	91.0	92.1	90.6	96.4	92.4	91.6
C/5 Delta V	0.6	0.3	0.3	0.5	0.3	0.3	0.3	0.4

*No cool down allowed before recharge.

"Delta V" numbers show maximum module voltage separation at the end of capacity testing. This separation has remained within an acceptable range throughout the testing.

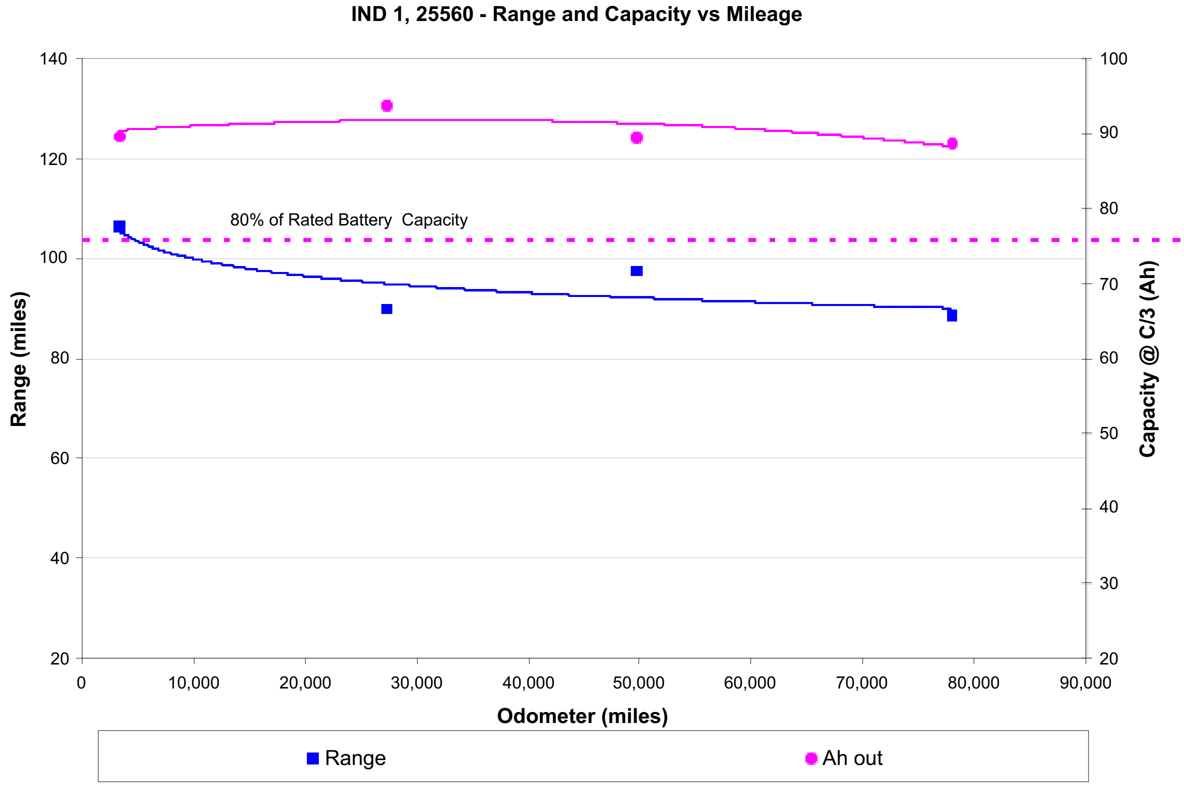

Figure 9 - IND 1, Range and Capacity versus Mileage

In Figure 9 battery capacity and vehicle range seem almost unaffected by mileage. Both IND 1 and IND 3 have operated well. Figure 10 shows capacity and range versus mileage. Both vehicles seem to retain good performance.

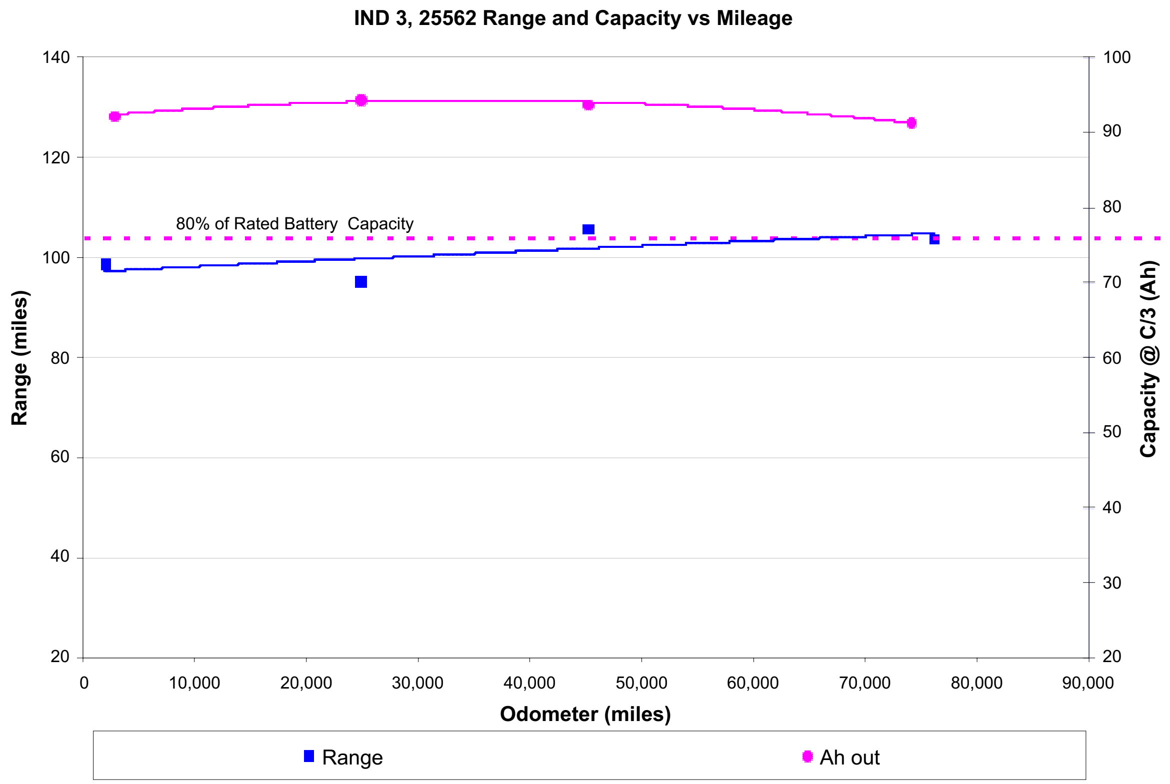

Figure 10 - IND 3, Range and Capacity verses Mileage

4. Findings

On November 8, 2002, CON 1 reached the goal of logging 100,000 miles with an original battery pack. Test data show that one battery module stopped the latest C/3 capacity test at 72.1 Ah, or 76% of nominal battery capacity, while driving range was still 81 miles or 86% of nominal miles.

CON 2 and CON 3 reached the 100,000 mile mark on February 4 and April 1, 2003 respectively. CON 2 has had three modules replaced. Tests show that range had decreased to 51 miles, while battery capacity was 85% of the nominal value. CON 3 has experienced an increase in battery capacity but achieved lower range.

The two inductive vehicles are expected to achieve the 100,000 mile goal by the end of 2003.

One lesson learned to-date has to do with thermal management of the batteries: To assure proper operation of the cooling system, periodic cleaning of air vent screens was recommended by SCE and approved by Toyota.

Data collected with the test vehicles and the RAV4 EV fleet, are confirming that EVs with Nickel Metal Hydride batteries, and a mature drive train design, are compatible with a variety of mission requirements. Not only are the EVs meeting the employees' driving needs, they are also very reliable, with little routine maintenance required.

5. Conclusions

The five-vehicle test is demonstrating the long-term durability of Nickel Metal Hydride batteries and electric drive trains. Only slight performance degradation has been observed to-date on four out of five vehicles. CON 2 EV, as discussed earlier, still has a capacity of 85% of nominal value but the range is 53 miles. A similar loss in range was experienced by CON3 EV but was successfully recovered. EVTC test data provide strong evidence that all five vehicles will exceed the 100,000-

mile mark. SCE's positive experience points to the very strong likelihood of a 130,000 to 150,000-mile Nickel Metal Hydride battery and drive-train operational life. EVs can therefore match or exceed the lifecycle miles of comparable internal combustion engine vehicles.

In June 2003 the 320 RAV4 EVs of the SCE fleet were used primarily by meter readers, service managers, field representatives, service planners and mail handlers, and for security patrols and carpools. In 5 years of operation, the RAV4 EV fleet had logged more than 6.9 million miles, eliminating about 830 tons of air pollutants, and preventing more than 3,700 tons of tailpipe carbon dioxide emissions.
Given the successful operation of its EVs to-date, SCE plans to continue using them well after they all log 100,000-miles.

6. References

1. SCE Report No. TC-00-01108-TR05
2. SAE Procedure No. J1634 – EV energy consumption and range testing

7. Authors

Thomas J. Knipe – Team leader, Battery Technology and Laboratory Operation

Mr. Knipe is responsible for the testing and evaluation of advanced battery technologies and is safety coordinator at the EV Technical Center. Mr. Knipe is also investigating the near and long term effects of high power charging on traction batteries. He has 16 years experience in testing, maintenance and installation of stationary and motive power batteries and six years in testing advanced batteries for EVs, ground support equipment, bicycles, scooters, and battery pack management systems. He received full qualification by the GM school for EV maintenance and coordinates training at the EVTC.

Loïc A. Gaillac, M.S.

Mr. Gaillac is a project lead in advanced energy storage at SCE's Electric Vehicle Technical Center and evaluates vehicles, batteries, and chargers in cooperation with manufacturers, government and industry. Two of his recent projects included one for the United States Advanced Battery Consortium (USABC) to determine the cycle life of advanced battery technologies in stationary applications. The other was for the Advanced Lead Acid Consortium (ALABC) and evaluated the cycle life of lead acid batteries under fast charging. Before joining SCE, Mr. Gaillac was employed by PSA ("Peugeot Société Anonyme", a French automaker). Mr. Gaillac has a B.S. degree in Electrical Engineering and a M.S. degree in Power Electronics and Control System from a leading graduate school in France.

Juan C. Argueta - Manager, EV Technical Center

Mr. Argueta is responsible for the operation of SCE's state-of-the-art Electric Vehicle Technical Center. His overall duties include the allocation of resources to on-going operations and special projects taking place at the Center. In addition, Mr. Argueta serves as Management Representative for the Center's ISO 9001-2000 Quality Management System. Mr. Argueta has been an active member of the electro-drive industry since joining SCE in August of 1992. He holds a Mechanical Engineering degree from the California State University in Los Angeles and a Master's in Business Administration from the University of Southern California.